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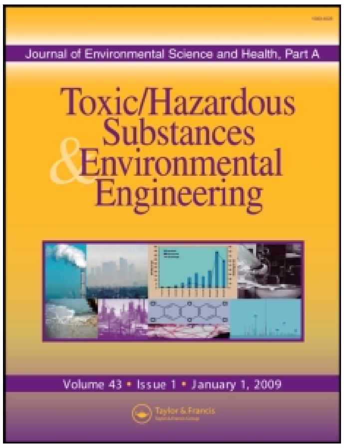

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Prediction of Dimethyl Disulfide Levels from Biosolids Using Statistical Modeling

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Prediction of Dimethyl Disulfide Levels from Biosolids Using Statistical Modeling

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Two statistical models were used to predict the concentration of dimethyl disulfide (DMDS) released from biosolids produced by an advanced wastewater treatment plant (WWTP) located in Washington, DC, USA. The plant concentrates sludge from primary sedimentation basins in gravity thickeners (GT) and sludge from secondary sedimentation basins in dissolved air flotation (DAF) thickeners. The thickened sludge is pumped into blending tanks and then fed into centrifuges for dewatering. The dewatered sludge is then conditioned with lime before trucking out from the plant. DMDS, along with other volatile sulfur and nitrogen-containing chemicals, is known to contribute to biosolids odors. These models identified oxidation/reduction potential (ORP) values of a GT and DAF, the amount of sludge dewatered by centrifuges, and the blend ratio between GT thickened sludge and DAF thickened sludge in blending tanks as control variables. The accuracy of the developed regression models was evaluated by checking the adjusted R^2 of the regression as well as the signs of coefficients associated with each variable. In general, both models explained observed DMDS levels in sludge headspace samples. The adjusted R^2 value of the regression models 1 and 2 were 0.79 and 0.77, respectively. Coefficients for each regression model also had the correct sign. Using the developed models, plant operators can adjust the controllable variables to proactively decrease this odorant. Therefore, these models are a useful tool in biosolids management at WWTPs.

Key Words: Dimethyl disulfide; Biosolid odors; Statistical modeling.

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INTRODUCTION

Wastewater treatment is an important environmental function that produces biosolids as a by-product. These solids, after proper treatment in accordance with U.S. Environmental Protection Agency (EPA) regulations,[1–3] can then be applied beneficially to farms, forests, tree farms, and mines due to their returning nutrients and organic matter to these reuse sites. This is especially meaningful due to erosion and loss of organic matter from traditional farming activities.[4]

In spite of the beneficial uses of biosolids, certain groups perceive these products adversely. The main argument is that the biosolids are malodorous as well as having other concerns about public health and the water supply.[5] Wastewater treatment plants (WWTPs) can be proactive in their management of these negatively perceived aspects by examining the factors that, for instance, lead to malodorous biosolids. It is believed that the smelly aspects are caused principally by reduced sulfur and nitrogenous compounds.[6] The odorous sulfur compounds such as dimethyl disulfide (DMDS), carbon disulfide (CS_2), and dimethyl sulfide (DMS)[7] smell like rotten cabbage and have low human sensory odor thresholds (0.01–1 ppbv[8,9]). Two compounds make up the majority of the nitrogen-containing biosolids odors: ammonia (NH_3) and trimethyl amine (TMA). Ammonia has a medicinal odor and TMA a fishy one.[9,10]

There are two main methods for measuring biosolids odors. First, one can take samples at a WWTP and analytically measure the actual amounts of DMS, DMDS, and other relevant compounds under laboratory conditions. This is generally a time-consuming approach given the nature of the testing as well as the need to have representative samples. Examples of this approach include D'Amato and DeHollander[11] who summarized recent efforts in managing biosolids odors at WWTP; Kim et al.[12] who investigated lime-stabilized bisolids from WWTPs and demonstrated that the production of TMA can be increased when polymer and protein material are added to dewatered, limed biosolids; Murthy et al.[13] who also concluded that polymer causes the release of TMA during the lime stabilization process. Later, Murthy et al.[14] and Novak et al.[15] analyzed the effect of lime under TMA and DMDS odor emissions. Kim et al.[16] analytically evaluated anthraquinone and $Ca(NO_3)_2$ usability in reducing odors from post-limed biosolids. Lastly, Kim et al.[8] and Arispe et al.[17] presented a solid phase microextraction method for detection of odorous gases from the wastewater treatment process with detection limits comparable to that for humans.

Alternatively, odors can be evaluated with human odor sensory panels. Odor evaluation using an odor panel (usually comprising six to eight individuals) is divided into two, based on the ways of sample introduction to the panel; a direct odor sniffing method and a dynamic olfactory method. In direct odor-sniffing method each individual, who directly smells the samples, then records scores as to the levels of perceived odors; usually from zero (none) to five (extremely offensive). In dynamic olfactometry, once odor samples are taken, they are transported to a remote laboratory, where they are introduced to an odor panel through equipment that can dynamically dilute the gas samples with odor-free air.

Having biosolids odors concentration or scores using either the analytic or the odor panel approach, the next step is to gather data on independent variables such as ambient or effluent temperature, sludge blanket the depth levels, amount of chemicals added in the treatment process, etc. This aim of this paper is to statistically identify a model relating the dependent variable, biosolids odor levels (or related compounds), to a subset of these ambient or processing related variables. Armed with such a model, WWTPs can proactively adjust their inputs (e.g., choice and amount of chemicals, modifications to processes) in combination with ambient conditions to lower the biosolids odors whenever possible. In this way, society as a whole will benefit from the reuse of material high in organic carbon, but these operations can be carried out with lower perceived negative aspects.

In this paper, two statistical models were developed to predict DMDS levels in biosolids sampled from the Blue Plains WWTP operated by the District of Columbia Water and Sewer Authority (DCWASA). To develop the models, odorants from biosolids produced from the plant and process variables were measured in headspace samples collected over one year. Since the results are novel, they should assist WWTPs with better management of the malodorous aspects of biosolids.

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MATERIALS AND METHODS

Overview of the Blue Plains WWTP

The Blue Plains facility is the major municipal WWTP in the Washington, DC metro area, which includes areas of Maryland and Virginia. This WWTP produces over 1200 dry tons per day of biosolids, all of which are currently beneficially recycled for agricultural purposes.

Wastewater influent flow initially passes thru bar screens for trash removal and is then treated with iron salts ($FeCl_3$) for phosphorus removal. The large $FeCl_3$ dose added to the wastewater at this stage could potentially affect the odors emitted by the final biosolids product downstream and was considered in the statistical model as an independent variable. After dosing with iron salts, grit is removed (settled) from the wastewater as the flow passes through grit chambers. The wastewater continues to flow to the primary sedimentation tanks.

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Primary Process

Organic suspended solids and phosphorus are removed from the wastewater flow by slowing the flow and allowing gravity settling in primary sedimentation tanks. The scum that floats to the surface in these tanks is skimmed off and combined with the settled solids on the bottom. Both scum and settled solids are next processed for additional removal of detritus and then gravity thickened. The thickened solids are pumped to the blend tank. The primary wastewater effluent flows to secondary reactors.

Secondary Process

Primary effluent flows in a step feed mode to the secondary aeration reactors where the effluent is mixed with $FeCl_3$ for additional phosphorus removal and with secondary and nitrification return activated solids (RAS). The amount of $FeCl_3$ added is one of the independent variables that could affect downstream biosolids odors and was considered in the statistical modeling. This mixture (mixed liquor) is aerated in the secondary reactors and aerobic microorganisms are grown at a high rate to remove suspended and colloidal carbon, and phosphorus. The mixed liquor from the aeration reactors flows to the secondary sedimentation tanks and the solids are gravity settled. The level (blanket level) of the solids that build up in these sedimentation tanks is one of the independent variables that could affect downstream biosolids odors and was considered in the statistical modeling. A portion of these settled solids (RAS) are returned to the aeration reactor. The rest of the settled solids are pumped to dissolved air floatation (DAF) thickeners. The secondary effluent flows to the nitrification/denitrification process.

Nitrification/Denitrification

The nitrification/denitrification process removes nitrogen from the secondary effluent. Methanol and return activated solids from the nitrification sedimentation tanks are mixed with secondary effluent (mixed liquor) in the nitrification reactors. This flow is processed through a series of aerobic and anoxic tanks for the conversion and removal of ammonia and organic nitrogen to N_2 gas. The mixed liquor subsequently flows to sedimentation tanks and the solids are gravity settled. A portion of these settled solids (RAS) are returned to the nitrification reactor and the rest of the settled solids are pumped to DAF thickeners.

DAF

Settled solids from the secondary and nitrification/denitrification sedimentation tanks are pumped to DAF tanks and mixed with compressed air and polymer to coagulate and thicken the solids. The addition of polymer may result in the final limed biosolids emitting fishy (TMA) odors and therefore the amount of polymer added was considered as a variable in the statistical modeling. After thickening the solids are pumped to the blend tanks.

Blend Tank

Gravity-thickened primary solids and DAF thickened secondary are mixed together in the blend tank. Primary and secondary solids are first stored in separate tanks and are then fed at a calculated blend ratio into the blend tank. Since this ratio may have an effect on the final biosolids odor level, the ratio was considered as an independent variable in the statistical modeling.

Dewatering and Lime Stabilization

The solids from the blend tank are mixed with polymer and then dewatered by high solid centrifuges and belt presses. Again, the addition of polymer may result in the final limed biosolids emitting TMA odors and the amount of polymer added was considered as a variable in the statistical modeling. The dewatered cake is then mixed with lime (CaO) for pathogen reduction complying to USEPA's Class B. The number of centrifuges in use and the amount of lime added could significantly affect the final biosolids odor and were evaluated as variables in the statistical modeling.

Sample Collection

Sludge sample collection was performed weekly from May, 2003 to May, 2004. Samples were obtained from several different locations within the plant solids-handling system with specific treatments shown in Table 1. Lime was

Table 1: Description of sludge treatment processes of the WWTP and sampling locations.

Abbreviation	Description	Sampling location
GR	Outflow from gravity thickener	Sample sink
DAF	Outflow from dissolved air flotation system	Sample sink
BS	Recycling line from Blending tank	Sample sink
BSP	Blended gravity and DAF sludge from blending tank with polymer added	Sample collection port just before centrifuge
DW	Dewatered sludge	Just after centrifuge, before conveyance
DWL	Dewatered sludge that has been limed in the laboratory	Just after centrifuge, before conveyance

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added into a subsample of dewatered sludge in the laboratory on site. Analysis of percent solids was performed in the laboratory immediately after collection. Based on the solid content determined, the lime dose was 20% by mass.

Extraction and Analysis of Odorous Chemicals

The headspace of samples was analyzed for a number of odorants including DMDS.[17] From each grab sample, 5 mg of dewatered sludge or 10 ml of liquid sludge was placed in a 20 ml clear glass vial, and sealed with an aluminum crimp top cap containing a Teflon-coated silicon septum. The target analytes were preconcentrated from the headspace of the sample using a technique called solid-phase microextraction (SPME) (Sigma-Aldrich Corp., St. Louis, MO). In SPME, a thin, coated fiber absorbs the organic chemicals from the headspace in proportion to their concentration. The fibers, which are coated with 75 μm carboxen-polydimethylsiloxane were exposed within the headspace for 1 h. After the exposure, fibers were transported (25 min) on dry ice to the U.S. Department of Agriculture (USDA) laboratory, where they were analyzed with the multidimensional gas chromatography-mass spectrometry (GC-MS). SPME fibers, which were not analyzed immediately, were preserved in a freezer at -40°C. None of the fibers were kept for more than 10 h prior to analysis. One blank sample vial containing only distilled water was included with each set of samples ($n = 10$) to observe any procedural interferences.[17]

When analyzed, the fibers were desorbed in the injection port of the GC. The multi-dimensional GC-MS system allows for cryogenic cutting of peaks from a nonpolar phases column in the first GC oven prior to further separation and improved chromatography on a more polar Carbowax column in second oven. The system consists of two 6890N (Agilent Technologies, Inc., Palo Alto, CA) gas chromatographs (GC); see Figure 1. The first GC (GC-1) is equipped with a flame ionization detector (FID) at a temperature of 250°C, where the

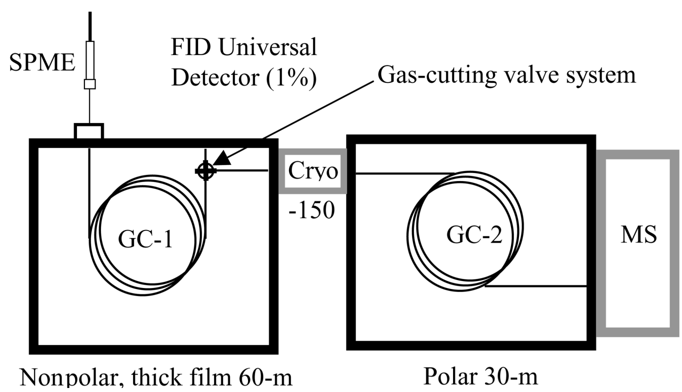

Figure 1: Schematic diagram of GC system used.

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detector is used as a monitor for methods development. The column for GC-1 is a 30 m HP-1 (Agilent Technologies, Inc.), with an inner diameter of 0.32 mm and a phase thickness of 1 μm. The second GC (GC-2) installed with a 30-m DB-Wax column (Agilent Technologies, Inc.) with an inner diameter of 0.32 mm and a phase thickness of 0.5 μm, is connected to an Agilent 5973 Mass Selective Detector (MSD) at a temperature of 300°C. The MSD was operated in selective ion mode to monitor the ion masses of the DMDS, i.e., 45, 79, and 94. GC-1 and GC-2 were connected through a Gerstel CTS1 Cryotrap System (Gerstel, Inc., Baltimore, MD), with a 1-m-long HP-5 column (Agilent Technologies, Inc.), 0.32 mm inner diameter, and a phase thickness of 0.25 μm. The injection port of the GC system was equipped with a 0.75 mm injection port liner and a Merlin microseal septum (Sigma-Aldrich Corp., St. Louis, MO) specially designed for SPME.

The temperature program on each GC for the analysis of DMDS is as follows: initially, GC-1 holds at 32°C for 3 min, and ramps at 3.5°C/min to 118°C, then at 50°C/min to 270°C. GC-2 initially holds for 13.5 min at a temperature of 32°C, ramps at 5°C/min to 45°C, holds for 2 min, ramps at 5°C/min to 90°C, and then at 63°C/min to 250°C, and finally holds for 1 min.

SPME Fiber Calibration Procedures

Preparation of the standard gases of DMDS used in SPME calibration was done using a certified Teflon membrane permeation device (NIST traceable, VICI Metronics, Inc., Santa Clara, California, USA) as described by Arispe et al.[17]. The developed standard curve for DMDS showed good linearity ($R^2 = 0.991$) within the range between 0.4 and 585 ppbv. The detection limit for the method used in this study, i.e., 0.4 ppbv was two orders of magnitude lower than the reported human sensory odor threshold (12 ppbv).[8] The reproducibility of the suggested method was evaluated in the former study. Errors less than 7% were observed between different fibers and between different injections, showing good reproducibility of the suggested method.[8]

RESULTS AND DISCUSSION

As described in the previous section, one year's worth of approximately weekly data (May 2003–May 2004) were collected resulting in separate observations by compound. In addition to measuring the concentration of DMDS and other compounds that were present, data on potentially useful variables such as the oxidation reduction potential were gathered. In what follows, a brief description of the set of independent variables that were available that might influence DMDS; hence, biosolids odor levels are presented.

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AMBIENT AND PROCESS VARIABLES

Oxidation-Reduction Potential

Oxidation-reduction potential (ORP) is used as an indicator of the overall oxidation state of a system, in this study wastewater and sludge. The lower the ORP the more reduced (septic) conditions and the higher the generation of reduced sulfur compounds from wastewater sludge.[18] This study concentrated on sludge before the dewatering process. Therefore, three ORP variables were used: ORPs of gravity thickened and DAF thickened sludge, and ORP for sludge from the blend tank. The ORP measurements were carried out by dipping an ORP probe (Mettler Toledo model Type 405-SC-DPAS, Woburn, MA, USA) in sludge aliquots of 200 mL right after they were collected. ORP is expected to have a negative correlation with biosolids odors, hence increased DMDS concentrations.

Temperature of Primary Effluent

Temperature of the sludge can affect ORP as well as microbial activity in wastewater treatment.[18] Research has shown that more odorous compounds are released from wastewater sludge during the summer as compared to the winter[18] due in part to ORP from gravity thickened sludge and DAF sludge which are lower during the summer.[8] Thus, the temperature of the primary effluent could be influential on the microbiological activity and ultimately on odor generation. All things being equal, one would expect this temperature to be positively correlated with DMDS levels.

Concentration of Iron from $FeCl_3$ and Waste Pickle Liquor

Arispe[18] showed that the concentration of iron left in biosolids has a negative correlation with odor from lime stabilized biosolids. Since $FeCl_3$ and waste pickle liquor (WPL) are the major chemicals used to remove phosphorous in the primary and secondary processes, respectively, the concentration of iron in the flow from these two chemicals could have an effect on DMDS levels and hence biosolids odor. Concentration of iron in the flow (mg/l) is computed in terms of mg of iron from $FeCl_3$ or WPL per liter of flow into the primary and secondary processes, respectively. It is anticipated that the concentration of either WPL iron or $FeCl_3$ iron will be negatively correlated with DMDS levels.

Number of Centrifuges or Belt Presses in Service

At the Blue Plains WWTP, sludge from the blend tank is dewatered in order to reduce the water content before hauling to the field sites. There are two units operating the dewatering processes. Dewatering is done either by DCWASA or by an onsite contractor. At least 150 dry tons of sludge are assigned to the contractor with the remainder dewatered by DCWASA. If there are not enough DCWASA centrifuges operating when there is a high volume of sludge to be treated, the process will come inefficient. As a result, biosolids having sufficient water might allow more sustained micro organic activity and greater levels of odor could result. At the Blue Plains facility, there are seven centrifuges available for the DCWASA processing as well as two centrifuges and seven belt filter presses for use by the contractor. All things being equal, one would expect the higher the number of centrifuges and belt filter presses operating, the lower the resulting biosolids odors or DMDS levels.

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Millions of Gallons per Day of Sludge Dewatered by Centrifuges

The amount of sludge treated per centrifuge could be an important variable in explaining biosolids odors. Overloading may cause higher liquid percentages in biosolids and thus ultimately more odor generation. Consequently, the ratio of production per centrifuge can be used to monitor dewatering status on any given day. A positive regression coefficient for this parameter is expected.

Sludge Blanket Depth in Secondary Settling Tank

The sludge blanket depth indicates the amount of waste activated sludge sitting at the bottom of the secondary settling tank. In the secondary process, microorganisms use air from the aeration tank to break down organic matter. Then, the wastewater is sent to the settling tank to separate suspended solids from wastewater. The accumulation of sludge in the settling tank is measured as the blanket level in the tank. The assumption on the sludge blanket is that the higher the blanket depth in the tank, the greater the biosolids odor generation. The rationale is that all things being equal, a higher blanket depth is due to a longer retention time for the sludge in the settling tank. This causes anaerobic conditions as well as reduced ORP at the bottom of the tank. As a consequence, when septic solids from the secondary settling tank are combined with solids from the primary process in the blend tank, the greater biosolids odors can be produced. There are three sludge blanket depth variables available at the Blue Plains facility: blanket depth "east," blanket depth "west odd," and blanket depth "even." A positive regression coefficient for sludge blanket depth is anticipated.

Blend Ratio in Blend Tank

This variable is the ratio of two amounts of sludge. The numerator is the quantity of sludge from gravity thickeners. The denominator is the quantity of sludge from the DAF tank. As most sludge from gravity thickeners contains organic material, it will serve as a food source for microorganisms when combined with the sludge from the DAF in the blend tank. All things being equal, a higher ratio implies a greater amount of food for microorganisms that will cause more production of sulfur compounds. As a result, the blend ratio should be positively correlated with DMDS levels.

Polymer Added

The enzymatic breakdown of protein and polymer in sludge causes the production of DMDS and TMA in lime stabilized biosolids.[16] There are two locations of polymer used in the solids handling processes: polymer additions in DAF and polymer additions in the dewatering process. The purpose of polymer in DAF is to facilitate the thickening capacity of sludge. As in the dewatering process, polymer is used to improve dewatering capacity in the centrifuges. At the Blue Plains WWTP, DAF polymer and dewatering polymer are used to monitor the effect of polymer on biosolids odor. One would expect the amount of polymer to be positively correlated with biosolids odors.

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Statistical Results

Based on the set of available independent variables outlined here, many statistical models were tried. Three factors were used to evaluate the quality of the models. First, the adjusted R^2 measuring the quantity of variation in the dependent variable (DMDS levels) explained by the model should be as high as possible. Second, the sign of the coefficients for the independent variables outlined above should be correct. Third, these coefficients should be statistically distinct from zero with fairly high confidence (e.g., *p*-value of 0.20 or less). After a series of models were tried, the two best ones are shown below.

Model 1 shown in Table 2, is of the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4, \tag{1}$$

where

Y = DMDS ppmv/ DMDS odor threshhold ppm

X_1 = ORP from gravity thickener sample (ORP_GR) (mv)

X_2 = ORP from DAF sample (ORP_DAF) (mv)

X_3 = amount of sludge dewatered by a centrifuge, gallons per day per centrifuge (mgd/centrifuge)

X_4 = blend ratio^2

and β_0, β_1, β_2, β_3, β_4 are the associated coefficients estimated by least squares with β_0 the intercept estimate. This model shows coefficients with the correct signs which are statistically distinct from zero (at the 0.02 level or better) and a

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Table 2: Summary of statistical analysis for the regression model number 1.

Summary	Muliple	R-square	Adjusted S-square	Standard error of estimate	Durbin Watson
	0.9076	0.8238	0.7944	3.845563	2.2031

ANOVA table	Degrees of freedom	Sum of squares	Mean of squares	*F*-ratio	*p*-value
Explained	4	1659.028	414.757	28.0462	<0.0001
Unexplained	24	354.9205	14.78835		

Regression Table	Coefficient	Standard error	*t*-value	*p*-value	Lower limit	Upper limit
Constant	−41.3114105	5.97848	−6.9100	<0.0001	−53.650388	−28.97243331
ORP_GR	−0.0751423	0.02129	−3.5295	0.0017	−0.1190827	−0.031201934
ORP_DAF	−0.10409707	0.022084	−4.7136	<0.0001	−0.149677	−0.058517089
MGD per centrifuge	19.91889631	7.943908	2.5074	0.0193	3.52347564	36.31431699
Blend ratio^2	19.4558089	3.066747	6.3441	<0.0001	13.1263548	25.78526299

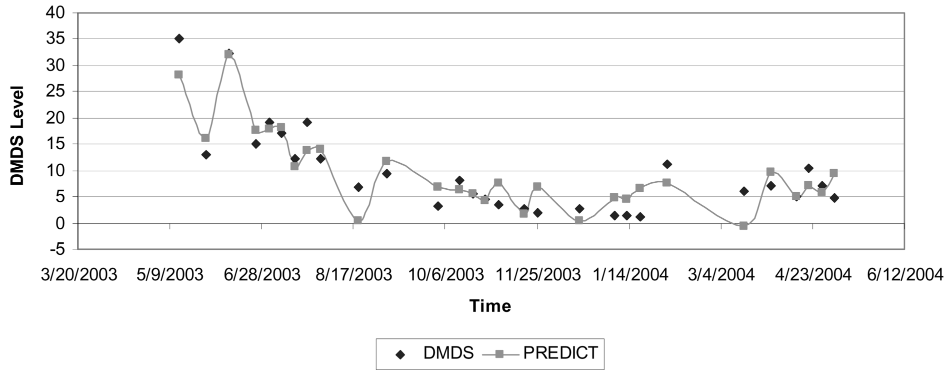

Figure 2: Model 1, actual vs. predicted DMDS levels.

large (adjusted) R^2 (79.44%)[1]. It is important to note that one of the observations had a DMDS level of 48.09. This value was over 3.4 standard deviations away from the average level of 10.92. As such, this value represented an outlier whose elimination could be justified on the grounds that the model was only valid for less extreme values. Doing so, the regression improved dramatically. Figure 2 shows a graph of how well this model predicted actual DMDS levels.

Since the units for the variables are different, one cannot directly compare the relative coefficients in Table 2 to gauge the influence of each variable on DMDS levels. Two ways around this are to either normalize the data to have the same range for each independent variable or to compute an elasticity for each independent variable. Elasticity measures how much the dependent variable (DMDS level) changes as a percentage with a percentage change in the independent variable value.[19] The associated elasticities for the independent variables are provided in Table 3 and indicate the following. First, ORP_DAF has the largest effect on increasing the DMDS levels. A 10% decrease from its average value leads to almost a 31% increase in DMDS (holding all other variables at their average value) [2]. This should be compared with ORP_GR, which is about 14%. These observations are reasonable since in the case of DCWASA, DAF thickeners are fed with waste activated sludge, which drives the system ORP more negative and creates a more septic environment. Also important to notice is the nonlinear effect of the blend ratio. Namely, the higher the blend ratio value, the greater the production of microorganisms producing DMDS and at an accelerating rate.

[1]Note that the coefficients for the variables are only valid within the ranges of practical operations. For example, for the variable *blend ratio*^{2}, the range is $(0.5)^2$ to $(2.0)^2$.
[2]These elasticity computations involved multiplying the average value for the variable by 1.1.

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Table 3: Elasticity analysis for the regression model number 1.

	% increase in DMDS level
10% decrease in ORP_GR	14.38
10% decrease in ORP_DAF	30.97
10% increase in MGD per centrifuge	6.09
10% increase in blend ratio	11.89

A second model was chosen from the best ones with slightly different variables. In particular, Model 2 was of the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 \tag{2}$$

where

Y = DMDS ppmv/ DMDS odor threshhold ppm

X_1 = ORP from gravity thickener sample (ORP_GR) (mv)

X_2 = ORP from DAF sample (ORP_DAF) (mv)

X_3 = amount of sludge dewatered by a centrifuge, gallons per day per centrifuge (mgd/centrifuge)

X_4 = an interaction variable, blend ratio*(-ORP_DAF)

X_5 = a dummy variable for when the blend ratio was greater than 0.6 (80% fractile)

and $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are the associated coefficients estimated by least squares with β_0 the intercept estimate. Two items about the variables chosen are of note. First, the interaction of the blend ratio variable with ORP_DAF and a dummy

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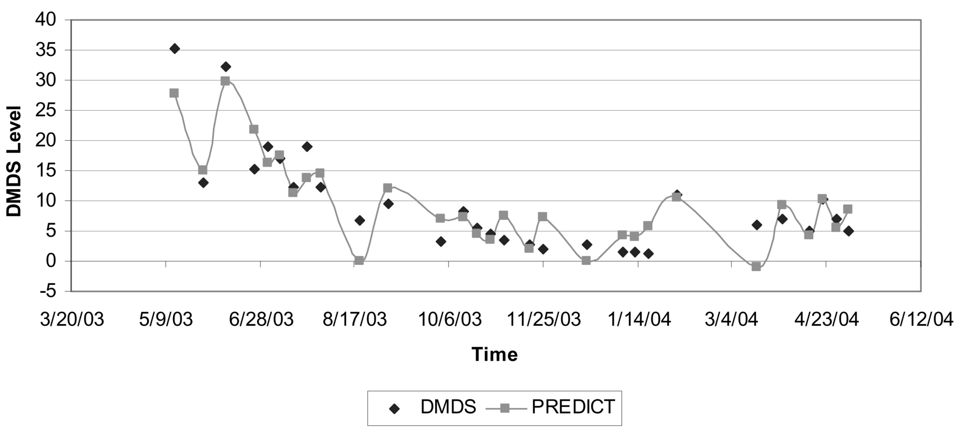

Figure 3: Model 2, actual vs. predicted DMDS levels.

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Table 4: Summary of statistical analysis for the regression model number 2.

Summary	**Multiple**	**R-square**	**Adjusted R-square**	**Standard error of estimate**	**Durbin Watson**
	0.9004	0.8108	0.7696	4.070478757	2.4772

ANOVA table	**Degrees of freedom**	**Sum of squares**	**Mean of squares**	**F-ratio**	**p-value**
Explained	5	1632.866009	326.5732017	19.7101	<0.0001
Unexplained	23	381.0823382	16.56879731		

Regression table	**Coefficient**	**Standard error**	***t*-value**	***p*-value**	**Lower limit**	**Upper limit**
Constant	−38.76124984	6.511589269	−5.9527	<0.0001	−52.23149854	−25.29100115
ORP_GR	−0.064970536	0.022749442	−2.8559	0.0089	−0.112031343	−0.017909729
ORP_DAF	−0.092763488	0.025287673	−3.6683	0.0013	−0.145075025	−0.040451952
MGD per centrifuge	22.72167305	8.855238323	2.5659	0.0173	4.403216906	41.0401292
Blend*(-ORP_DAF)	0.044648498	0.02047995	2.1801	0.0397	0.002282494	0.087014501
BLEND > 0.6 (80%)	5.362356133	2.695584648	1.9893	0.0587	−0.213885564	10.93859783

Table 5: Elasticity analysis for the regression model number 2.

	% increase in DMDS level
10% decrease in ORP_GR	11.30
10% decrease in ORP_DAF	25.07
10% increase in MGD per centrifuge	6.31
10% increase in blend*(-ORP_DAF)	6.11

variable representing high levels of the blend ratio were included and replaced the squared blend ratio term in Model 1.

The interaction term, given as the product of the associated variables, measured the effect of their joint levels. Since ORP_DAF is negatively correlated with DMDS, but the blend ratio is positively related, the negative of the ORP variable was taken to ensure that this interaction term had a positive coefficient to check for appropriateness. As was the case with Model 1, the outlier was taken out. Figure 3 shows a graph of the actual DMDS levels and what was predicted by Model 2 and Table 5 indicates the elasticities of the independent variables. It is important to note that this model also has a relatively large adjusted R^2 (76.96%), as well as coefficients that were of the right sign and statistically distinct from zero. The ORP_DAF variable also has the largest influence on DMDS production as shown in by its elasticity in Table 5. It is important to note the effect of the interaction variable which indicates that when the blend ratio is high and the ORP_DAF level is low, the combined effect can be significant in DMDS production. This is exacerbated when the blend ratio exceeds 0.60 consistent with the blend ratio dummy variable having a statistically significant positive value.

CONCLUSION

In this paper, two statistical models to predict levels of dimethyl disulfide (DMDS) have been developed that correlate with biosolids odors based on several operational and controllable variables. These models are an important tool for wastewater treatment managers since they allow them to adjust the control variables to produce lower DMDS levels. These models were based on data from laboratory experiments as well as operational statistics collected at the Blue Plains WWTP and considered a wide variety of variables to explain DMDS production. While the current work concentrated on investigating the relationship of certain ambient and processing variables to solids odors, future work will analyze statistical models for liquids odor production.

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